

THE TWO CENTRAL STARS OF NGC 1514: CAN THEY ACTUALLY BE RELATED? ^a

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ABSTRACT

The central star of the planetary nebula NGC 1514 is among the visually brightest central stars in the sky ($V=9.5$). It has long been known to show a composite spectrum, consisting of an A-type star and a much hotter star responsible for the ionization of the surrounding nebula. These two stars have always been assumed to form a binary system. High-resolution spectrograms obtained with Espadons at the CFHT on Mauna Kea have allowed to measure good radial velocities for both stars. They differ by $13 \pm 2 \text{ km s}^{-1}$. The stellar velocities have not changed after 500 days. We have also estimated the metallicity of the cooler star. Combining these data with other information available in the literature, we conclude that, unless all the published nebular radial velocities are systematically wrong, the cooler star is just a chance alignment, and the two stars are not orbiting each other. The cooler star cannot have played any role in the formation of NGC 1514.

Keywords: planetary nebulae: individual (NGC 1514) — stars: AGB and post-AGB — techniques: radial velocities

1. INTRODUCTION

NGC 1514 belongs to a small group of planetary nebulae with A-type central stars. Obviously in each of these cases a hotter star needs to be present, to explain the ionized state of the surrounding nebula. Thus the central star of NGC 1514 has always been assumed to be a binary system. We will not give an extended historical introduction on NGC 1514; the reader is directed to a recent paper by Aller et al. (2015).

That the central star spectrum is composite was shown by Kohoutek (1967), and confirmed spectroscopically by Greenstein (1972). Greenstein's spectra did not show any convincing velocity variation, but he did note that He II $\lambda 4686$ from the hot star showed a mean velocity difference of $-7 \pm 5 \text{ km s}^{-1}$ relative to the H and metal lines of the A-type star. Other observers have given conflicting reports on radial velocity variations. According to Seaton (1980), this was not satisfactorily resolved. Since then, it appears that nobody ever tried again. We have obtained new high-resolution spectrograms of this central star, and report the resulting radial velocities in what follows. Section 2 describes the observations. Section 3 explains how the velocities were measured, and presents the results. In Section 4 we give a preliminary estimate of the metallicity of the cooler star. In Section 5 we discuss all the information we have collected, and Section 6 recapitulates the conclusions.

2. THE ESPADONS SPECTROGRAMS

Espadons is a bench-mounted, high-resolution echelle spectrograph, fiber-fed from a Cassegrain unit at the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii. Spectrograms of the 9th-magnitude central star of NGC 1514 were obtained in Star+Sky mode ($R=68000$) and normal CCD readout mode, with individual exposure times of 1740 seconds. Table 1 gives a list of the spectrograms taken for this project. The heliocentric Julian Dates correspond to mid-exposure. All the spectrograms were obtained by the CFHT staff in Queued Service Observing Mode.

^a Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

Table 1. Espadons spectrograms used in this work

Exposure Ident Number	Date	Heliocentric JD (UTC) (2450000+)	Heliocentric RV correction (km s ⁻¹)
1753905	Nov 05, 2014	6967.15142	+10.847
1753906		6967.16163	+10.831
1755174	Nov 08, 2014	6970.07856	+09.544
1755175		6970.08877	+09.522
1756502	Nov 12, 2014	6973.96764	+07.859
1756503		6973.97784	+07.830
1769682	Dec 20, 2014	7011.69743	-11.020
1769683		7011.70763	-11.038
1771245	Dec 29, 2014	7020.69252	-15.241
1771246		7020.70272	-15.262
1895441	Feb 20, 2016	7438.71453	-29.608
1895442		7438.73515	-29.656

2.1. Reductions and description

The spectrograms were fully processed by CFHT using the UPENA software. This software calls the Libre-Esprit pipeline (Donati et al. 1997). We have used the normalized ASCII tables provided by CFHT (filenames ending ...in.s), each of which provides the extracted, sky-subtracted, wavelength-calibrated spectrum, with rectified continuum, and with heliocentric radial velocity correction applied. Therefore, measurements of wavelengths of any features on these spectra can be directly transformed into heliocentric radial velocities.

2.2. Spectral description of the hotter star

The spectrum of the cooler star has been sufficiently described in the literature (see e.g. Greenstein 1972 and Aller et al. 2015). The high spectral resolution and high signal-to-noise ratio of the Espadons spectra permit a good description of the hot star features. The following are clearly visible in absorption (all wavelengths in Å): He II 4200, 4541, 4686, 5411; N V 4603, 4619; O V 5114. There are also narrow emissions of C IV 5801, 5811, N IV 4057, N V 4944, O V 4930, and O VI 5290. These high-ionization C, N, O features, together with the absence of C III 5696, N III 4634, 4640, 4641, and O III 5592, indicate a very high surface temperature of this star, as expected from the 90,000 K estimated by Aller et al. (2015). The strength of the Balmer absorption lines from the A-type star makes it very hard to decide if the hotter star is H-deficient. There is no evidence of strong mass loss in the optical spectrum. If Aller et al. (2015) are correct, and some H is present on the surface, then the spectral type, in the system of Méndez (1991), is O(H).

Figures 1 and 2 show the result of co-adding the 12 Espadons spectrograms. For brevity we show only the most interesting spectral features of the hot star. The sharpness of the C, N, O features indicates that $v \sin i$ and the macroturbulent velocity must be rather low, and that no large-amplitude radial velocity variations can be expected in the available sample. A more detailed spectral analysis is deferred to future work.

3. RADIAL VELOCITY MEASUREMENTS

Because of the composite nature of the spectrum, we decided to measure spectral features individually, rejecting any features where contamination from the other star can be expected. For example, some He II absorption profiles are distorted by other absorptions from the A-type star, or other features, and were not used. N V 4619 was rejected for the same reason. Table 2 lists the adopted wavelengths of all the spectral features measured for radial velocity on the individual spectra. We selected only the highest quality, symmetric profiles.

Radial velocities were measured in the following way. First, it was necessary to create a new ASCII table for each spectrum, with equally spaced wavelengths always taken from a unique prespecified set. The intensities corresponding to each wavelength in the prespecified set were obtained from the original spectrum by a standard interpolation routine.

The next step was to co-add all the spectra; this co-added spectrum is the source of the plots shown in Figures 1

Table 2. Spectral features measured for radial velocity

Star	Element	Wavelength (Å)	
Cooler	Mg II	4481.228	ab
Cooler	Fe II	4508.27	ab
Cooler	Fe II	5018.434	ab
Cooler	Fe II	5316.69	ab
Cooler	Si II	6347.091	ab
Hotter	N IV	4057.759	em
Hotter	N V	4603.73	ab
Hotter	O V	5114.07	ab
Hotter	C IV	5801.33	em
Hotter	C IV	5811.98	em

Table 3. Heliocentric radial velocities of the cooler star in km s⁻¹

Exposure Ident Number	Mg II 4481	Fe II 4508	Fe II 5018	Fe II 5316	Si II 6347	Heliocentric JD (UTC) (2450000+)
1753905	45.0	46.2	48.8	43.9	41.6	6967.15142
1753906	44.4	44.7	48.3	43.6	42.9	6967.16163
1755174	43.8	43.8	45.6	41.4	40.5	6970.07856
1755175	45.2	45.1	46.3	39.8	41.5	6970.08877
1756502	44.9	47.2	47.3	41.8	43.3	6973.96764
1756503	45.1	45.5	48.1	41.4	43.0	6973.97784
1769682	44.2	42.7	47.6	41.0	42.8	7011.69743
1769683	43.6	41.6	46.3	39.9	43.1	7011.70763
1771245	44.4	43.9	46.5	40.8	44.5	7020.69252
1771246	44.0	45.7	46.1	41.0	42.9	7020.70272
1895441	44.6	44.9	47.4	41.4	42.9	7438.71453
1895442	45.0	44.7	47.6	41.8	44.6	7438.73515

and 2. Then, on the co-added spectrum, for every spectral feature in Table 2 a Gaussian was fitted, and the peak of the Gaussian was used to calculate the heliocentric radial velocity, in km s⁻¹, to be used as reference. The goodness of the Gaussian fit was always checked interactively.

Finally, the individual velocities for each feature and for each individual spectrum were calculated by cross-correlating against the corresponding feature in the co-added spectrum. Tables 3 and 4 give the results for the cooler and hotter star, respectively.

4. THE METALLICITY OF THE COOLER STAR

Armed with our high-resolution co-added spectrogram, we can study the metallicity of the cooler star. As discussed by Aller et al. (2015), for the observed combination of $T_{\text{eff}} = 9850$ K and $\log g = 3.5$, we have two alternatives: a horizontal branch star, or a more massive star evolving away from the main sequence. But the horizontal branch star, to be hot enough, must have a low metallicity. For example, the evolutionary tracks used by Aller et al. were

Table 4. Heliocentric radial velocities of the hotter star in km s⁻¹

Exposure Ident Number	N IV 4057	N V 4603	O V 5114	C IV 5801	C IV 5811	Heliocentric JD (UTC) (2450000+)
1753905	59.0	57.3	57.8	55.4	57.6	6967.15142
1753906	59.0	57.5	57.7	54.9	57.1	6967.16163
1755174	54.8	58.0	57.9	55.1	56.7	6970.07856
1755175	58.2	57.9	58.8	55.1	56.7	6970.08877
1756502	58.1	56.7	58.3	55.0	56.7	6973.96764
1756503	60.3	56.8	57.5	55.5	56.5	6973.97784
1769682	56.7	56.8	57.8	55.9	57.0	7011.69743
1769683	59.6	56.9	58.1	55.5	57.6	7011.70763
1771245	56.1	56.9	56.8	55.4	57.3	7020.69252
1771246	58.6	56.9	57.2	55.1	56.9	7020.70272
1895441	57.6	56.6	56.5	54.5	56.7	7438.71453
1895442	57.2	56.2	56.5	54.5	56.0	7438.73515

calculated with $Z = 0.006$. Another way of seeing this would be to look at Figure 2.2 in Ashman & Zepf (1998), where they compare color-magnitude diagrams of two globular clusters with different metallicities ($[\text{Fe}/\text{H}] = -1.7$ and -0.6). The more metal-poor cluster shows a well-populated horizontal branch at $(B-V)=0$, while the other has nothing at that position.

Therefore, a sufficiently accurate measurement of metallicity can be used to test if the cooler star can be a horizontal branch star. To obtain the spectrum of the cooler star, we adopted the ratio of fluxes shown in Figure 5 of Aller et al. (2015), subtracted the contaminating light from the hotter star, and renormalized. The spectrum obtained in this way was compared with synthetic normalized spectra calculated with line-blanketed model atmospheres and very detailed NLTE line formation calculations (Przybilla et al. 2006). Similar models have been successfully used by Kudritzki et al. (2008, 2012) to study medium-resolution spectra of supergiant stars in nearby galaxies.

Synthetic spectra were calculated for $\log g = 3.5$; a pair of temperatures, $T_{\text{eff}} = 9700$ K and 10,000 K, bracketing the temperature determination of Aller et al. (2015); and a pair of metallicities: $[Z] = \log(Z/Z_{\odot}) = 0.0$ and -0.6 . For a definition of this $[Z]$ we refer e.g. to Kudritzki et al. (2008).

To apply these synthetic spectra to a comparison with our Espadons spectrogram, the synthetic spectra were degraded to the instrumental resolution, and further broadened with a $v \sin i$ of 50 km s^{-1} , obtained from the renormalized profiles of a few blend-free absorption lines in the spectrum of the cooler star. The results of the comparison of observed versus synthetic spectra can be appreciated in Figures 3 and 4. The observed profiles of metal lines fall, on average, in between the two corresponding synthetic profiles. We conclude that for the cooler star $[Z]$ is approximately -0.3 . We defer a more careful determination to future work, where we expect also to measure abundances in the hotter star. For the moment, Figs. 3 and 4 confirm that the metallicity of the cooler star is too high for a horizontal branch star. Therefore, it must be a more massive (around $3 M_{\odot}$), and more luminous star, at a distance of at least 400 pc (Aller et al. 2015). We hope that very soon the Gaia mission will be able to test this prediction.

5. DISCUSSION

The average velocity of the cooler star in Table 3 is $44 \pm 2 \text{ km s}^{-1}$. The average velocity of the hotter star in Table 4 is $57 \pm 1 \text{ km s}^{-1}$. The small differences between the average velocities from the different lines are probably due to small errors in the laboratory wavelengths. The velocities of the two stars differ significantly, by $13 \pm 2 \text{ km s}^{-1}$. None of the two stars have shown substantial velocity variations.

Assume the two stars are orbiting each other. The different velocities indicate that we cannot be observing the orbits pole-on. Then the lack of variations of the order of 10 km s^{-1} in almost two years would require a long orbital period. The results in Tables 3 and 4 can be used to reject all previous claims or suggestions of high-amplitude, short-period

radial velocity variations (e.g. as discussed by Muthu & Anandarao 2003 in their section 5). This implies that the cooler star cannot have played any direct role in the formation of NGC 1514, e.g. through a common envelope episode.

There is some additional information to be extracted from the existing literature.

5.1. *Radial velocity of the cooler star*

The only previous study at high spectral resolution is by Greenstein (1972). There are coude spectrograms from 1949 to 1971. The average radial velocity ($47.6 \pm 1.6 \text{ km s}^{-1}$) looks quite in agreement with the values reported in Table 3. The Greenstein velocities are not directly comparable to those in Table 3, because he included several lines we have rejected, like the Balmer lines; did not give the velocities for each spectral feature separately; nor did he report what laboratory wavelengths he used. But given the dispersion of values listed in his Table 1, and his conclusion (no sign of velocity variation, in his own words), it is reasonable to conclude that there is no reliable evidence of variations in the velocity of the cooler star in six different epochs from 1949 to 2016.

5.2. *Radial velocity of the hotter star*

In Greenstein's paper the velocity of He II 4686 is mentioned to be more negative than that of the Balmer lines and the metals by $7 \pm 5 \text{ km s}^{-1}$. He did not elaborate on this, so probably he did not consider the difference to be significant.

The velocity we measured on the co-added Espadons spectrum for He II 4686 is 52 km s^{-1} . We did not include velocities from this line in Table 4 because the profile is affected by what appears to be an unidentified emission line at 4688 \AA (see Figure 1). Another reason to avoid this line as a radial velocity indicator is that it is among the first, in the visible spectral range, to suffer the effects of a stellar wind. Even a very incipient P Cygni-like profile would induce a shortward wavelength displacement in the observed absorption (Kudritzki et al. 2006).

Continuous monitoring for at least a decade would be required to verify if Greenstein's data were implying long-period variability of the hotter star's velocity.

5.3. *Radial velocity of the nebula*

According to Schneider et al. (1983), the heliocentric radial velocity of NGC 1514 is $60 \pm 4 \text{ km s}^{-1}$ (an average of six different determinations, each with a reported uncertainty of between 3 and 9 km s^{-1}). This is perfectly compatible with the velocity of the hotter star in Table 4.

Two velocities in Schneider et al. are discrepant: one substantially above the average, and one below it. The one above can be ignored, because of its lower accuracy. The one below is more interesting: it is $41 \pm 5 \text{ km s}^{-1}$, from Greenstein (1972). There is a way of understanding the discrepancy. Greenstein reports that the spectrograms he used to measure the nebular velocity were taken with the slit located one arc minute south of the central star. There is a spatiokinematic study of NGC 1514 by Muthu & Anandarao (2003), made with a Fabry-Perot spectrometer. Unfortunately they did not attempt to measure the absolute radial velocity; but they do show velocity channel maps (their Figure 4). In this figure we find that slightly less than one arc minute south of the central star there is a concentration of gas with a velocity of -13 km s^{-1} . There is no corresponding gas at the opposite velocity ($+13$). That is conceivably the reason why Greenstein's nebular velocity was more negative.

Anyway, it is fair to say that systematic errors in the published nebular velocities cannot be completely discarded. Integral field spectroscopy of NGC 1514 at high spectral resolution would permit to accurately map the whole velocity field, and produce a more reliable number for the systemic radial velocity of this planetary nebula.

5.4. *Binary system or chance alignment?*

Since the radial velocities of the two central stars differ, and the nebular velocity agrees with that of the hotter star, there is a distinct possibility of chance alignment with the cooler star. This would be extremely surprising, because Ciardullo et al. (1999) were unable to resolve the pair on Hubble Space Telescope (HST) images. The probability of such a perfect chance alignment is extremely low, of the order of 10^{-8} (using an area of 0.01 square arc second, and an estimated surface density of 10 stars of 10th visual magnitude per square degree at the galactic latitude of NGC 1514, which is 15 degrees). See e.g. Figure 4 of Bahcall & Soneira (1980).

In dealing with such a low probability, every possible alternative, however unlikely, must be considered. Our anonymous referee has kindly provided a few.

Let us first consider if the velocity of the hotter star could be higher because of gravitational redshift. This would require its $\log g$ to be around 7.5. But this replaces one problem with another: since the hotter star is rather bright, its distance from us would have to be much less than 50 pc, ruling out any association with the cooler star.

Table 5. Radial velocity amplitudes for different periods

Period (years)	$a_1 + a_2$ (R_\odot)	$K_1 + K_2$ (km s^{-1})
1	329	46
10	1529	21
30	3180	15
100	7096	10

Next, imagine that the velocity of the cooler star is different because of a recoil effect produced in a binary system when NGC 1514 was formed. The problem here is that, in order to produce a substantial recoil effect, the orbital period would have to be longer than the time scale for nebular ejection. But for such long orbital periods, the orbital velocities would not be enough to explain the observed velocity difference between the two stars (a few examples are given in Table 5, to be explained below).

Finally, under what conditions can the two central stars of NGC 1514 be members of a binary system? In Section 4 we concluded that the cooler star must be rather massive, around $3 M_\odot$. Assume a typical central star mass of $0.6 M_\odot$ for the hotter star. If these two stars are orbiting each other, the nebular velocity must be close to the velocity of the cooler star. In other words, all the nebular measurements discussed in the previous subsection would have to be systematically wrong.

Consider the value of the sum of the radial velocity semiamplitudes as a function of the orbital period. Table 5 shows the values of the sum of the orbital semimajor axes ($a_1 + a_2$) and the sum of the radial velocity semiamplitudes ($K_1 + K_2$) as functions of the orbital period, using Newton’s version of Kepler’s 3rd law, with a total mass of $3.6 M_\odot$, and using the relation between semiamplitude, orbital period, semimajor axis and eccentricity. Taking an orbital inclination of 53 degrees and an eccentricity $e=0.6$, the factors $\sin i$ and $(1 - e^2)^{0.5}$ cancel each other. Unfavorable (smaller) values of inclination would produce smaller numbers in the third column of Table 5. An orbital eccentricity $e=0.7$ would increase those third-column numbers by a factor 1.4. But on the other hand, most of the time, the stars would be far from periastron, and the velocity difference between the two stars would be actually smaller.

Table 5 suggests an upper limit of about 50 years on the possible orbital period. Any longer period would require a value of $K_1 + K_2$ smaller than the observed velocity difference of 13 km s^{-1} . It will not take more than a few decades to decide conclusively if these two stars can actually be related.

5.5. Radial velocities: summary and consequences

The Espadons spectrograms show that the radial velocities of the two central stars of NGC 1514 are clearly different. The constancy of these high-quality velocities over a time of two years permits to reject all previous claims or suggestions of substantial short-term changes in the stellar velocity. Even if they orbit each other, the implied separation between the two stars precludes any past evolutionary interaction like a common-envelope episode. For all practical purposes, these two stars are evolutionarily unrelated. On the other hand, if they orbit each other, arguing from Kepler’s 3rd law, given the observed velocity difference, we do not expect an orbital period longer than about 50 years.

If new measurements of the nebular radial velocity confirm the values reported in the literature, which agree with the radial velocity of the hotter star, we will have to conclude that, unlikely as it may seem, the cooler star is a chance alignment. There is the problem that Ciardullo et al. (1999) could not resolve the two stars on their HST images. If there is a significant difference in the proper motions, then we would expect that sooner or later the two stars will become resolvable. In 1791 William Herschel reported that the star was perfectly in the center of NGC 1514 (see e.g. Greenstein 1972), and it still is today. The proper motion of the cooler star, measured by the Hipparcos satellite, is $8.4 \text{ milliarcsec/yr}$. This amounts to about 1.7 arcsec since the time of Herschel. On the other hand, the galactic longitude of NGC 1514 is 165 degrees, i.e., almost in the anticenter direction; so it would not be terribly surprising to find the two stars, even if at somewhat different distances from us, having similar proper motions. What is required now is a new observation with the highest possible angular resolution, which we expect to make in the near future.

The results reported here do not preclude the existence of low-amplitude velocity variations; both stars could have planetary systems or low-mass companions. Only future measurements of comparable or higher quality will tell.

6. RECAPITULATION

The Espadons spectrograms have permitted a much better spectral description of the hotter central star in NGC 1514 than previously available. On these new spectra it has been possible to measure the radial velocities of the two central stars. They are different, by about $13 \pm 2 \text{ km s}^{-1}$. No evidence of radial velocity variations has been found in either star. The metallicity of the cooler star is incompatible with its belonging to the horizontal branch; the cooler star must be more massive, more luminous, and more distant. We hope the Gaia mission will soon test our prediction of a distance of at least 400 pc for the cooler star.

The published nebular velocities agree with the hotter star's velocity, but might be somewhat unreliable. If the two central stars of NGC 1514 are a binary system, then we expect the nebular velocity to agree more with the cooler star's velocity. If future measurements of the nebular velocity confirm its similarity to the hotter star's velocity, and if no evidence of mutual orbital motion becomes apparent in the next few decades, we will have to conclude that the cooler star is a chance alignment. In any case, the cooler star cannot have played any direct role in the formation of NGC 1514.

Acknowledgements. We would like to express our gratitude to the staff of the Canada-France-Hawaii Telescope, for performing the necessary observations in Queued Service Observing Mode, and for providing beautifully reduced spectrograms. We thank the anonymous referee for making several valuable suggestions.

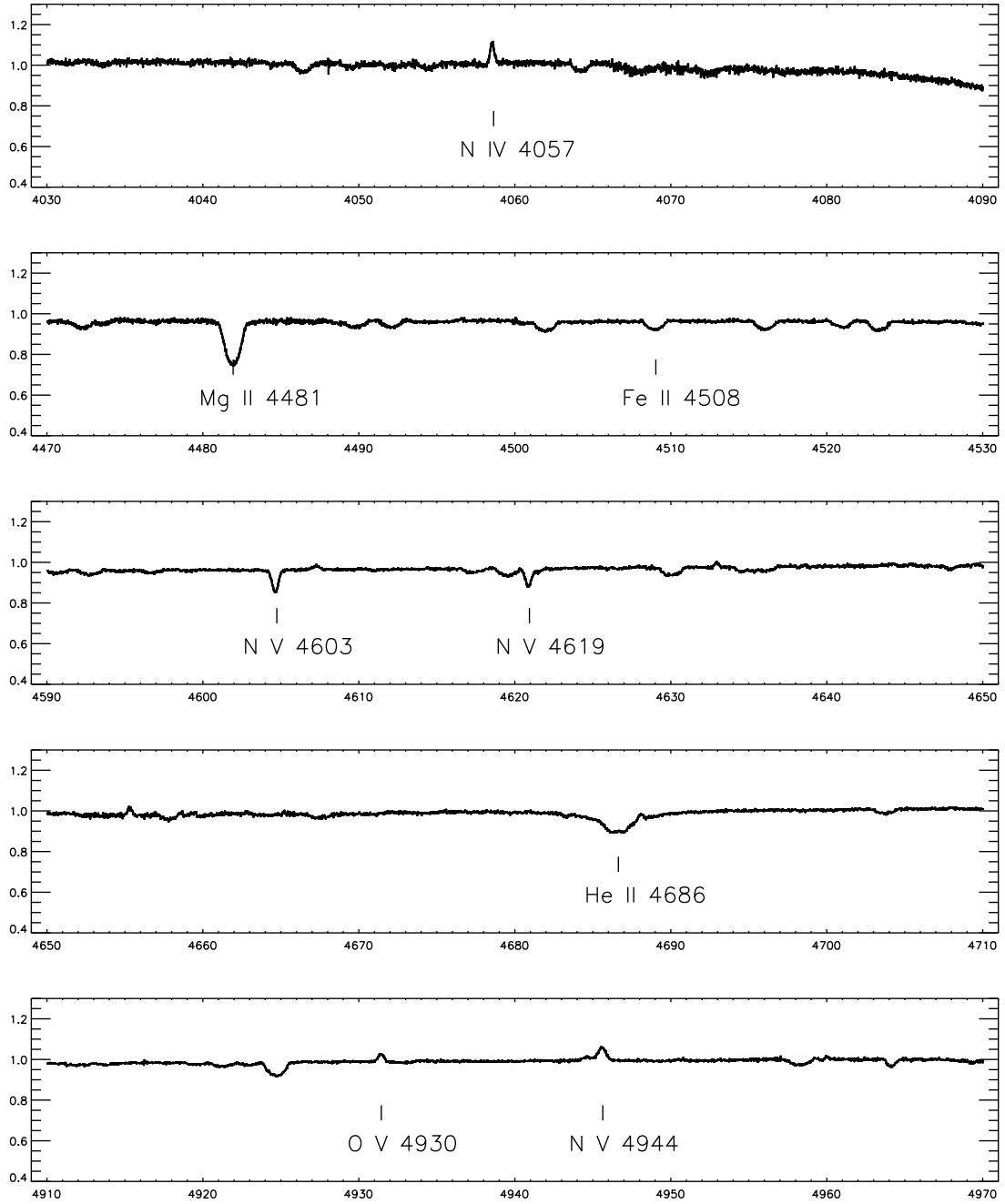


Figure 1. Selected features in the composite spectrum of the central stars of NGC 1514. The 12 Espadons spectra have been co-added. No attempt was made to optimize the continuum rectification. All wavelengths are in \AA .

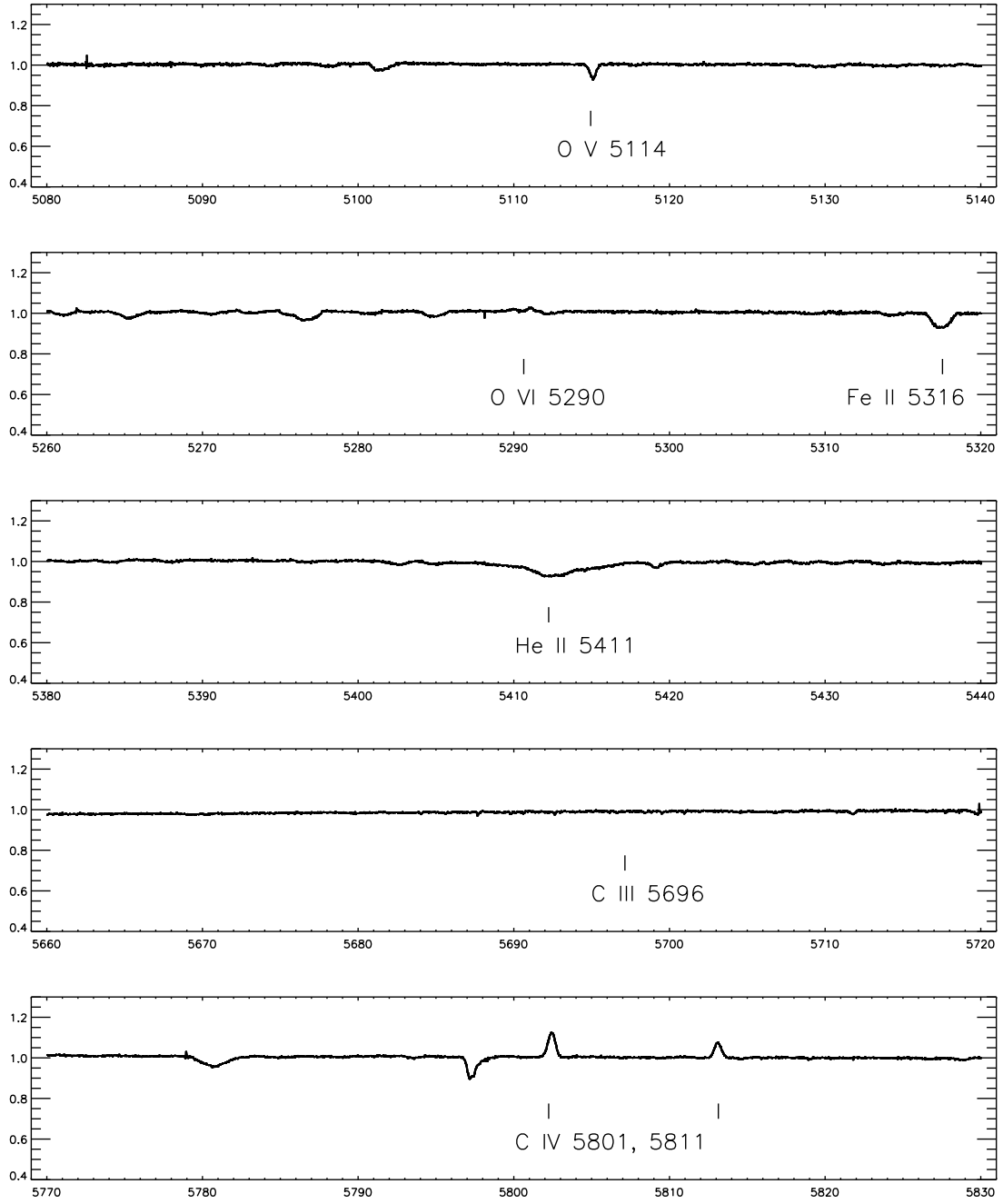


Figure 2. Selected features in the composite spectrum of the central stars of NGC 1514. The 12 Espadons spectra have been co-added. No attempt was made to optimize the continuum rectification. All wavelengths are in Å.

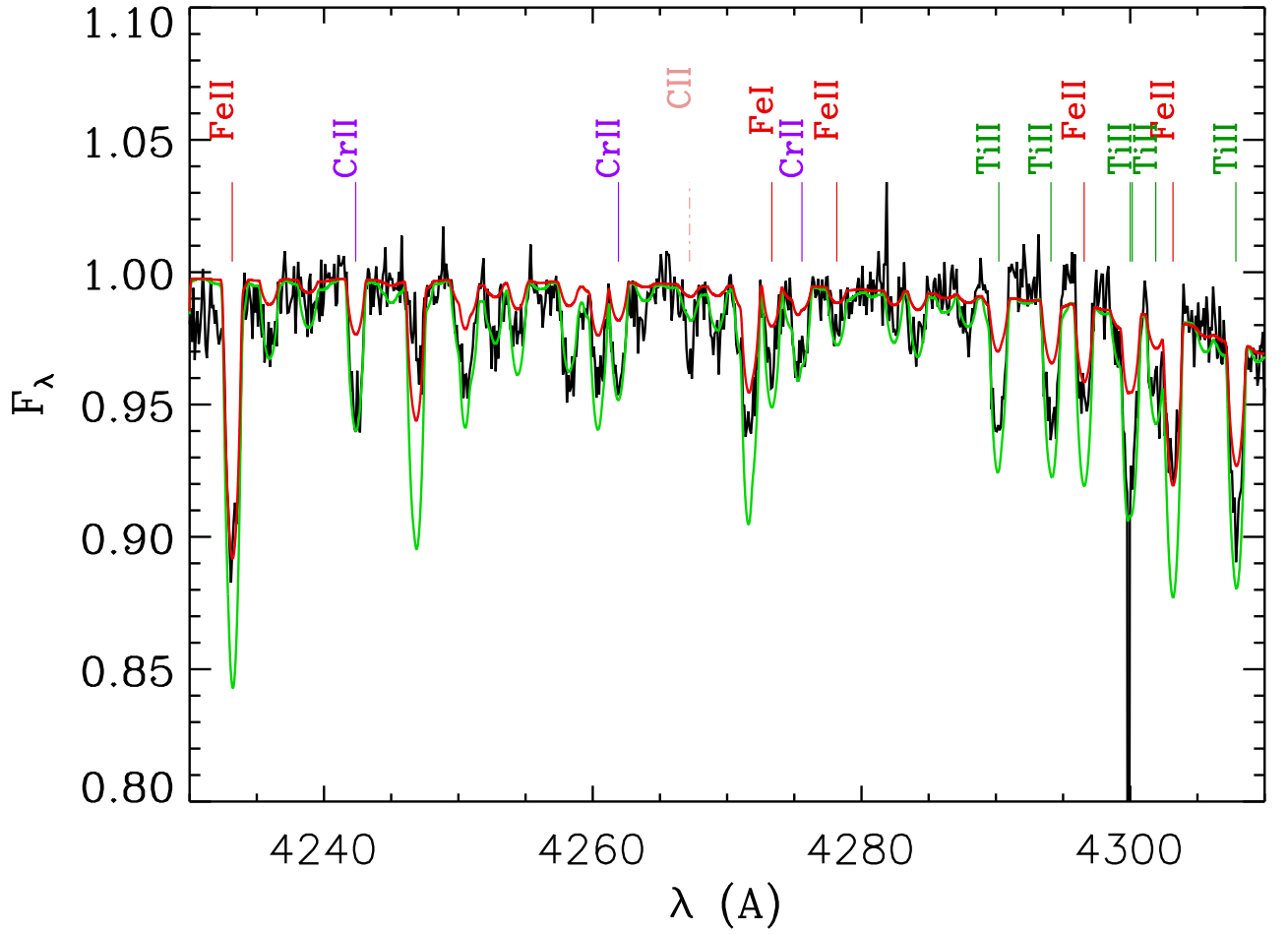


Figure 3. Comparison of the observed spectrum of the cooler star versus synthetic spectra for $\log g = 3.5$, $T_{\text{eff}} = 9700$ K, and two metallicities, $[Z]=0.0$ (green) and -0.6 (red). On average, we estimate the cooler star has a $[Z]$ of about -0.3 .

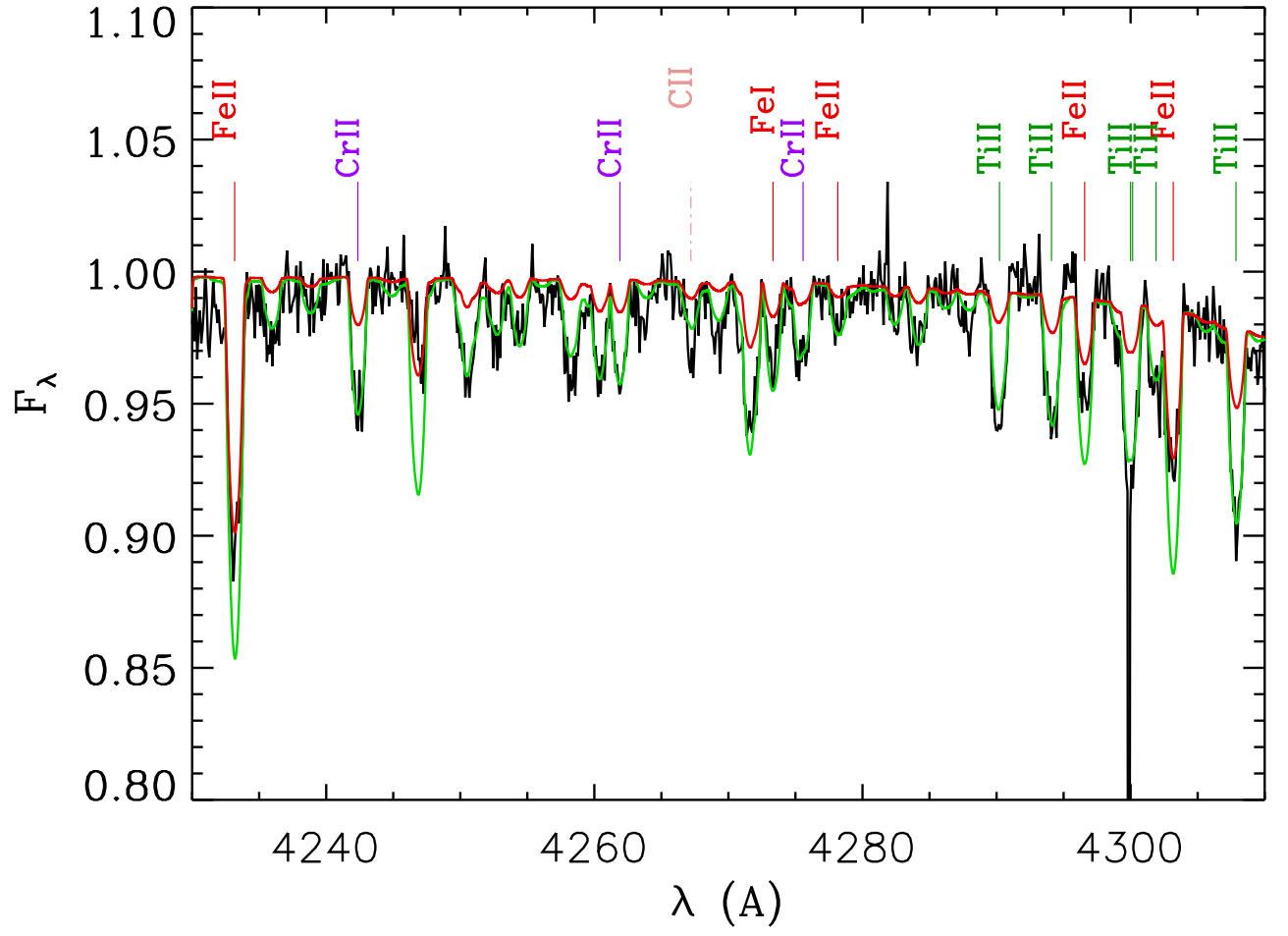


Figure 4. Same as Figure 3, but with $T_{\text{eff}} = 10,000$ K.

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